

157
ANODE-CATALYST PROMOTED REACTIONS OF
REFORMED HYDROCARBON FUEL CELL FEEDS

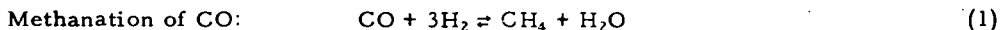
D. K. Fleming, S. S. Randhava, and E. H. Camara

Institute of Gas Technology
Chicago, Illinois 60616

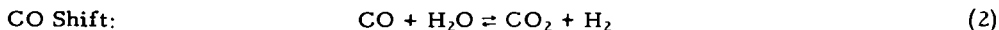
INTRODUCTION

The purpose of this study was to investigate the reactions of anode feed mixtures over candidate anode catalyst combinations. Previous work indicated that some of the catalysts suggested for CO-tolerant anodes were active in promoting chemical reactions of carbon monoxide with other constituents in the normal anode fuels. A program was initiated to determine if these reactions could occur at the operating temperature of the fuel cell with catalysts which had been formulated into fuel cell anodes with Teflon binder. The relative extent of these reactions could illustrate the mechanism of carbon monoxide tolerance in electrodes and indicate the formulations required for improved anodes.

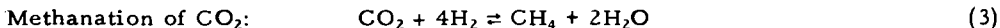
The methanation of carbon monoxide with hydrogen was one of the major reactions expected.



This reaction is the reverse of the reforming reaction and, according to free energy considerations, should proceed to the right at lower temperatures.



Another expected reaction is the CO shift. Equilibrium considerations dictate that the steady-state concentration of CO is about 1700 ppm at 150°C, if the $\text{H}_2\text{O}/\text{CH}_4$ ratio fed to the reformer is 2.5. With dry fuel, the equilibrium carbon monoxide concentration is higher by a factor of 10. There is an electrochemical equivalent of this reaction in which the product hydrogen is directly oxidized. This reaction may take place in an operating fuel cell because the hydrogen formed is adsorbed on the electrocatalysts.



Reaction 3 indicates the direct methanation of carbon dioxide and is the sum of Reaction 1 and the reverse of Reaction 2. However, this reaction need not occur stepwise with the formation of free carbon monoxide.

Other chemical reactions are also possible; however, these reactions have little likelihood of occurring at the fuel cell operating temperature and the C-H-O composition employed.

In this paper only the relative strength of the anode catalysts for enhancing these reactions is presented. No attempt is made to relate to the CO tolerance of operating fuel cell anodes, except in general terms with known past histories of anode performance.

Catalyst Selection

All of the anode catalysts used in this study were manufactured by American Cyanamid Co. according to its standard techniques, but with the noble metal constituents specified below. The noble metal loading in all electrodes was 5 mg/sq cm; the oxide admixture proportions followed the supplier's standard specifications. In mixed catalysts the weight proportions were evenly divided

between the constituents. The catalysts were not analyzed for precise composition; rather, the compositions requested from the supplier are discussed below.

The anode catalysts tested were —

- Platinum: This is the standard fuel cell catalyst and was used as a basis of comparison for the other materials.
- Ruthenium: This material is known to be active for the methanation reaction (Equation 1) when deposited on alumina. It provides the basis of comparison for platinum-ruthenium mixtures (1, 2, 4, 7).
- Rhodium: Pure rhodium is known to be slightly active in promoting the methanation reaction (2, 4) and provides a basis for comparison with platinum-rhodium mixtures.
- Platinum-Rhodium: This is the standard Type-BA catalyst manufactured by American Cyanamid and mentioned in its basic patent by Ziering, L. K. (8). Studies of this electrode were also conducted by McKee et al. (5).
- Platinum-Rhodium + WO₃: This is Cyanamid's Type-RA anode; it is discussed in the Ziering, L. K., patent (8) and by R. G. Haldeman (3), also of American Cyanamid Co.
- Rhodium + WO₃: Although not a standard anode catalyst, excellent carbon monoxide tolerance was claimed for this combination in the Ziering, L. K., patent (8) of American Cyanamid Co.
- Platinum-Ruthenium: This is the basic mixture used by General Electric Company. Several papers have been published on its carbon monoxide tolerance (4, 7).
- Platinum-Ruthenium + WO₃: This combination was selected because of the high activity of the platinum-ruthenium and the beneficial effects of the addition of WO₃ in other catalysts.
- Ruthenium + WO₃: This catalyst combines the best features of the ruthenium and the WO₃ admix, without the dilution effect of the platinum.
- Platinum + WO₃: This was a basic reference catalyst to determine the effects of the oxide constituents with a relatively inert base. This electrode combination exhibits carbon monoxide tolerance according to Niedrach and Weinstock (6).
- Platinum-Rhodium + MoO₃: Molybdic oxide was a constituent in the original precursor of the Type-RA electrode and was studied in this program to determine the effects of the MoO₃ admix.
- Platinum-Ruthenium + MoO₃: This combination was chosen to determine the effects of the molybdic oxide admixture upon the relatively active platinum-ruthenium noble metal base.

Palladium was not tested because it is relatively inert and iridium-containing electrodes could not be supplied. Variation of the noble metal proportions was not attempted in this study; varying concentrations of the oxide admixture were not available.

Table 1 lists the catalyst combinations used and the logical divisions according to systems and admixtures.

Table 1. CATEGORIZATION OF CATALYSTS TESTED

	Metals	Mixed Metals	Admixed Catalysts	
			WO ₃	MoO ₂
Rhodium System	Pt	Pt-Rh	Pt + WO ₃	Pt-Rh + MoO ₂
	Rh		Pt-Rh + WO ₃ Rh + WO ₃	
Ruthenium System	Pt	Pt-Ru	Pt + WO ₃	Pt-Ru + MoO ₂
	Ru		Pt-Ru + WO ₃ Ru + WO ₃	

Experimental Equipment and Techniques

The reactors for this work were standard fuel cell hardware, indicated schematically in an exploded view in Figure 1. Stainless steel and tantalum end-plates were tested and found inert for these reactions. The flow configurations in the 2 x 2 inch test cells were checked for uniformity by smoke tests. These electrodes were placed against a Teflon backup sheet and the available area of the electrode was determined by the opening in the frame gasket, identical to a standard fuel cell compartment gasket. Tantalum, expanded-metal screens were used to fix the location of the electrode.

The flow pattern of this reaction, with the reactant gas passing through a thin, wide chamber with one catalyzed wall, is not ideal. However, this is the configuration used in most fuel cells, and the equipment was set up to relate to operating fuel cells.

The tests were operated with dry electrodes; that is, an acid-soaked matrix was not present behind the electrode. The acid was omitted to avoid the effects of variable electrode drowning, gas dissolution rates, equilibrium shifts due to water at the electrodes, variable acid concentration with drying out of the cell, and other effects that would alter the rate and/or the reproducibility of the reactions. The results presented, however, are useful in relating the relative activity of the catalysts - a factor which is not grossly affected by the presence of an electrolyte. However, in an operating fuel cell, the electrode operates at fixed potentials with respect to the electrolyte. This potential may shift the equilibrium due to the effect upon the free energy change.

The experimental apparatus is indicated schematically in Figure 2. In the flow system either standard fuel gas or a zero gas (for calibrating the instrument) is admitted to the system through a pressure regulator and block valve. The gas passes through a flow-indicating rotometer and a flow regulator which control a constant, downstream flow rate, regardless of the upstream pressure. The gas then flows either to the test cell or to a bypass. Leaving the system, the gas goes either to a bubble flowmeter or to the gas analysis train. The bubble flowmeter is used to adjust the flow controller for each run. The gas analyzing equipment is calibrated with a zero and a standard gas at the beginning of each run. In a given test, when the cell temperature stabilized, as controlled by a proportional temperature-indicating controller and verified by a strip-chart temperature recorder, the bypass valve is closed and the gas fed to the cell for several minutes to establish steady-state conditions. The carbon monoxide and methane contents in the effluent gas are then recorded as a function of temperature.

The gas compositions are determined by sensitive infrared analyzers calibrated for the detection of carbon monoxide and methane. The first unit in the analysis train is a Lira Model 200, manufactured by Mine Safety Appliances,

Pittsburgh, Pa. It has three carbon monoxide ranges with full-scale sensitivities of 100, 500, and 5000 ppm CO. Although the lower range is direct reading, non-linearity exists in the upper two ranges so that calibration curves are required. When used with these curves, the Lira IR analyzer continuously monitors the carbon monoxide concentration in the flowing gas stream with an estimated accuracy of 2% of full scale. The analyzer used for methane determination is a Lira Model 300, which has greater electronic drift so the absolute values of the methane concentrations are not as accurate. This unit has a single range of 0-6000 ppm methane.

The gas flow rate used in most of this work was 300 cu cm/min. This rate was chosen because it is near the lower range of the gas analyzing equipment. Lower flows are time-consuming, and this standard flow rate indicates the relative performances of the catalysts. For comparative purposes, this flow rate is approximately equivalent to 30 times the stoichiometric equivalent for 1-ampere current drain from this size cell, or 10 times the stoichiometric flow rate for 100 A/sq ft current density. The average residence time in the cell is approximately 3/4 second.

The primary feed gas was a simulated reformer product:

Hydrogen	79.7%
Carbon Dioxide	20%
Carbon Monoxide	0.3%

Gas of this composition may be expected after reforming and shifting reactions with a high H_2O/CH_4 ratio in the feed to the reformer. This gas composition was chosen because it is a possible fuel cell feed and is near the mid-range of the gas analyzing equipment in concentration.

In some tests, a reference gas containing 80% hydrogen and 20% carbon dioxide was used. This gas determines the effect of a carbon monoxide-free feed. Most of the tests were run with dry feed, although some were operated with 57°C dew point humidification to check the effect of moisture on the reaction.

PRESENTATION OF RESULTS

Interpretation of the Data

The relative capabilities of these catalysts in promoting the reactions are determined by the change in the CO and CH_4 concentrations in the effluent gas stream. Any increase in the CH_4 concentration is indicative of Reactions 1 or 3. If an increase in CH_4 concentration is accompanied by a corresponding decrease in the CO level, then Reaction 1 takes place.

A decrease in the CO concentration could mean either Reaction 1 or 2 occurs. As discussed above, a corresponding increase in the CH_4 level indicates Reaction 1. Any increase in CO content, without a change in the CH_4 level, indicates the reverse of Reaction 2.

The effluent from some rhodium-containing catalysts first shows a decrease in the CO content, with a corresponding increase in CH_4 . At higher temperatures, both the CO and CH_4 levels increase. This is interpreted as simple methanation of carbon monoxide at lower temperatures, followed by the reverse CO shift and continued methanation at higher temperatures. However, the methanation capabilities of the catalyst are weak, so the net CO content increases.

Figures 3 and 4 present the carbon monoxide and methane concentrations in the effluent from fuel-cell-type reactors containing "metal-only" catalysts. In the rhodium system, the electrode containing only platinum exhibited a slight reduction in the CO concentration (Figure 3) at higher temperatures; the platinum-rhodium electrode was similarly inert. A pure rhodium electrode showed a carbon monoxide generation of about 50-100 ppm above 225°C. In Figure 4, the platinum exhibited a methane generation which was not significant. Again, the platinum-rhodium was inert. The pure rhodium electrode, however, showed a definite methane generating capability.

In summary, the platinum and platinum-rhodium electrodes are essentially inert in the temperature range studied. The pure rhodium is a weak methanation catalyst, probably forming CH_4 from CO. It is also slightly active in promoting the reverse CO-shift reaction.

Metals - Ruthenium System

The performance of the ruthenium system metals is presented in Figures 3 and 4. As indicated above, the platinum reference electrode is almost inert; however, the pure ruthenium one is a definite methanation catalyst. The carbon monoxide concentration in the effluent from this electrode decreased rapidly at temperatures between 150° and 175°C. Similarly, the methane concentration in the effluent rose as the CO concentration decreased, indicating that the carbon monoxide was being methanated. At temperatures greater than 175°C, the methane concentration continued to increase; the graphs do not present enough evidence to indicate if carbon dioxide was being methanated directly, or if carbon monoxide was being formed from carbon dioxide and hydrogen by a reverse CO shift, while the high methanation capabilities of the electrode maintained a low CO concentration. At higher temperatures, the CO concentration in the effluent tended to increase slightly. This is in accordance with the equilibrium consideration.

The platinum-ruthenium mixed electrode also exhibited methanation capabilities (Figures 3 and 4) but the effect took place at a higher temperature. This indicates that the catalytic strength of the platinum-ruthenium electrode is not as great, probably because of the dilution effect of the platinum upon the ruthenium.

In summary, in the ruthenium system, the platinum electrode is inert, but the ruthenium electrode is active in promoting the selective methanation of the carbon monoxide. When the CO had been consumed, additional methane was still generated, indicating either a direct methanation of carbon dioxide, or activity for the reverse CO-shift reaction followed by enough activity for the CO-methanation reaction that the carbon monoxide concentration was maintained at a low level. The platinum-ruthenium electrode behaves similarly to the ruthenium electrode, although at higher temperatures.

Effect of Additives - Ruthenium System

Figures 5 and 6 present the CO and CH_4 concentrations from three platinum-ruthenium electrodes. One of these electrodes contained no admixtures, another contained tungstic oxide, and the third contained molybdic oxide. These graphs indicate that the tungstic oxide admix significantly improves the methanation capabilities of this electrode, dropping the temperature of reaction to about 150°C. The molybdic oxide admix, however, had no significant effect upon the electrode's methanation capabilities; it may even have decreased this activity at the higher temperature, as indicated in Figure 6. However, the MoO_3 admix did cause an increase in the CO concentrations at elevated temperatures (Figure 5), indicating that this electrode is active in promoting the reverse CO-shift reaction when used in conjunction with platinum-ruthenium.

Figures 7 and 8 show the CO and CH₄ concentrations in a series of ruthenium-containing electrodes, both with and without tungstic oxide admix. These graphs indicate that the Pt-Ru + WO₃ is even more active for the methanation reaction than the pure ruthenium electrode; the Ru + WO₃ is more active yet. In contrast, the Pt + WO₃ anode exhibits the same degree of inactivity as the pure platinum electrode.

Summarizing, tungstic oxide exhibits a definite synergistic effect in promoting the methanation reaction when used in conjunction with ruthenium-containing electrodes. Molybdic oxide admix may have a slight depressing effect upon the methanation reaction, but promotes the reverse CO-shift reaction.

Effect of Admixes - Rhodium Systems

The CO and CH₄ concentrations from three platinum-rhodium electrodes are given in Figures 9 and 10. One of the electrodes contains no admix, another contains tungstic oxide, and the third contains molybdic oxide admix. These graphs indicate that the tungstic oxide admix promotes the generation of methane. At temperatures less than 175°C, the methane apparently is formed from carbon monoxide, because the decrease in the CO concentration is equal to the increase in the CH₄ concentration. At elevated temperatures, the CH₄ concentration continues to increase: The CO concentration also increased, indicating catalytic activity for the reverse CO-shift reaction.

The molybdic oxide admix, however, promotes very little decrease in the CO concentration at lower temperatures, but apparently promotes the reverse CO-shift reaction at higher temperatures. In Figure 10, the amount of methane generated with the molybdic oxide admix is relatively high. This may be due to direct methanation of carbon dioxide. As indicated earlier, the platinum-rhodium electrode without admix is relatively inert.

Figures 11 and 12 present the CO and CH₄ concentrations for the family of rhodium-containing electrodes both with and without WO₃ admix. As indicated earlier, platinum, platinum-rhodium, and platinum + WO₃ are relatively inert; the pure rhodium electrode has slight activity for the methanation and reverse CO-shift reaction. However, with the addition of tungstic oxide, the activity of the platinum-rhodium electrode for the methanation and CO-shift reactions increases significantly. These graphs also illustrate the one irregularity which has been observed: The pure Rh + WO₃ electrode is not as active for the methanation or CO-shift reactions as the Pt-Rh + WO₃ catalyst. This effect may be real or due to an irregular catalyst sample.

Summarizing, tungstic oxide admix exhibits a definite synergistic effect in promoting the methanation and reverse CO-shift reactions when used in conjunction with rhodium-containing catalysts. However, pure platinum plus tungstic oxide is relatively inert. Molybdic oxide admix apparently promotes only the reverse CO-shift reaction, although it may have an effect on the direct methanation of carbon dioxide with platinum-rhodium based catalyst.

Effect of CO-Free Feed

Figures 13 and 14 present the carbon monoxide and methane concentrations in the effluent from a Pt-Ru + WO₃ electrode with both the standard feed gas containing 3000 ppm CO and with a CO-free feed. Apparently, the methane-generating capability of this catalyst is greater with a CO-free feed: No carbon monoxide is generated with this catalyst. At temperatures in the range of 125°-150°C, significant CH₄ is generated without apparent CO in the effluent. This is the range (with the 3000 ppm CO feed) where the CO concentration decreases and the CH₄ concentration increases in an apparent steady-state condition. The new data indicate that methane may be generated from carbon dioxide without an independent

CO intermediate. Earlier data indicated that free CO would be present in the indicated temperature range during the selective methanation of the carbon monoxide. However, with the CO absent from the feed, the carbon dioxide can methanate directly and apparently reacts at a lower temperature when CO is absent from the feed.

Figures 15 and 16 present carbon monoxide and methane concentrations for a platinum-rhodium + tungstic oxide electrode combination, both with and without carbon monoxide in the feed. Figure 15 indicates that the activity of this catalyst for the CO-shift reaction is constant; Figure 16 indicates the variation in the methane-producing capabilities of the electrode with the feedstock. Again, more methane is generated from a CO-free feed. Similar to the ruthenium-containing electrode, methane is generated in a temperature range where the CO/CH₄ ratio is much lower than was required for the 3000-ppm CO feed. Therefore, it appears that the CO₂ is methanating at lower temperatures, but, as the temperature increases, CO also methanates as the two lines of Figure 16 merge.

With the feed containing 20% hydrogen and 20% carbon dioxide, the direct methanation of carbon dioxide is indicated for both Pt-Ru + WO₃ and Pt-Rh + WO₃ electrodes. The methane generated at any temperature is greater than experienced with CO-containing fuels when selective methanation of the carbon monoxide is experienced before methanation of the carbon dioxide. With the rhodium-containing electrode, activity for the reverse CO-shift reaction was still evident as carbon monoxide was formed at higher temperatures. In this case, the methane-generating capabilities from the two feed streams became similar at elevated temperatures with higher CO concentrations, indicating methanation of the carbon monoxide generated.

Effect of Moisture

Several tests were made with the fuel gas humidified to 57°C; the dew point if the H₂O/CH₄ ratio fed to the original hydrocarbon reformer was 2.5. The water concentration in the feed caused the effects expected from equilibrium considerations. It reduces the methane generated over the catalysts in Reaction 1 and the CO generated by the reverse CO-shift Reaction 2. Extensive tests with moisture in the feed were not run because they did not aid in the general purpose of the program — determining the relative catalytic activities of candidate anodes in the reformed fuel mixtures.

Effect of Gas Flow Rates

Earlier work had shown that the methanation reaction was sensitive to contact time. Figure 17 presents the methanation capability of a pure ruthenium catalyst electrode as a function of flow rate. The temperature at which the majority of the carbon monoxide is methanated decreases from 160° to 130°C as the flow rate is decreased from 500 to 100 cu cm/min. These data indicate that, at flow rates normally employed at the fuel cell anode, the temperature of the reaction decreases so that significant methanation may occur. This is particularly true in the case of the CO-containing fuel in the pores of the electrode as longer residency time would be expected in this case.

Figure 18 presents a similar set of curves for the variation in the CO consumed, with the flow rate for a platinum-rhodium plus tungstic oxide electrode. In this case, the methanation capability of the electrode is improved with lower flow rates, enough to partially offset the CO-increasing tendency of the CO-shift reaction at higher temperatures. Again, significant chemical reactions could occur at the fuel cell operating temperature; the lowest flow rate on this graph is still stoichiometrically equivalent to over 300 A/sq ft.

Noble metal catalysts formulated into fuel cell anodes maintained their activity for the methanation reaction. Particularly, ruthenium-containing electrodes exhibited significant methanating capabilities; pure rhodium electrodes showed some methanation activity. Therefore, the Teflon waterproofing is not a significant deterrent to the reaction, nor is the alumina support used in granular methanation catalysts necessary for the reaction.

Ruthenium-containing electrodes are active for the production of methane. If carbon monoxide is present in the fuel, it is selectively converted to methane before the carbon dioxide reacts. If the feed is CO-free, CH_4 is generated directly from CO_2 in greater quantities than if CO was present. The ruthenium-containing electrodes appear to be inactive for the generation of CO from CO_2 , although this effect could be masked by the CH_4 -generating capability of the material.

Rhodium-containing electrodes are much less active for the generation of CH_4 from CO and CO_2 , but the reactions still take place. Pure rhodium electrodes appear to be relatively inactive for the generation of CO from CO_2 .

All the reactions tested were sensitive to flow rate, indicating that reaction time is an important parameter in the equipment configuration used.

The addition of molybdc oxide appears to enhance the production of CO from CO_2 with both rhodium- and ruthenium-containing electrodes. It has slight effect upon the CH_4 generating capabilities, except, perhaps, causing some production of CH_4 from CO , with Pt-Rh electrodes.

The addition of WO_3 to the electrode has a definite synergistic effect for every catalyst combination tested, except pure platinum. With the ruthenium-containing electrodes, the methanation capabilities were significantly improved. The methanation capabilities were also improved with the rhodium-containing electrodes; in addition, this constituent improved the generation of CO from CO_2 with the rhodium catalyst family.

ACKNOWLEDGMENT

The work reported in this paper was supported under subcontract from Pratt & Whitney Division, United Aircraft Corporation under the gas industry's TARGET program and whose support and permission to publish are gratefully acknowledged. In addition, the efforts of D. Hegyi in the collection of the data are appreciated.

1. Baker, B.S., Meek, J., Khan, A.R. and Linden, H.R., "Process for Generation of Hydrogen From Liquid Hydrocarbons for Use in Acid Fuel Cells," U.S. Patent Application Serial No. 461,298 (1965) June 4.
2. Baker, B.S., Huebler, J., Linden, H.R. and Meek, J., "Process for Selective Removal of CO From a Mixture of Gases," U.S. Patent Application Serial No. 701,036; continuation filed (1968) January 10.
3. Haldeman, R.G., "Electrode-Matrix Materials," Proc. 21st Annual Power Sources Conf. 1-3 Red Bank, N.J., PSC Publications Committee (1967).
4. McKee, D.W., "Interaction of Hydrogen and Carbon Monoxide on Platinum Group Metals," J. Catalysis 8, 240-49 (1967) July.
5. McKee, D.W., Niedrach, L.W., Paynter, J. and Danzig, I.F., "Electrocatalysts for Hydrogen/Carbon Monoxide Fuel Cell Anodes. Part II. The Platinum-Rhodium and Platinum-Iridium Systems," Electrochem. Technol. 5, 419-23 (1967) September-October.
6. Niedrach, L.W. and Weinstock, I.B., "Performance of Carbon Monoxide in Low-Temperature Fuel Cells Containing Oxide Catalysts," Electrochem. Technol. 3, 270-75 (1965) September-October.
7. Niedrach, L.W., McKee, D.W., Paynter, J. and Danzig, I.F., "Electrocatalysts for Hydrogen/Carbon Monoxide Fuel Cell Anodes. Part I. The Platinum-Ruthenium System," Electrochem. Technol. 5, 318-23 (1967) July-August.
8. Ziering, L.K. (assigned to American Cyanamid Co.), "Rhodium Catalyst and Fuel Cell," U.S. 3,357,863 (1967) December 12.

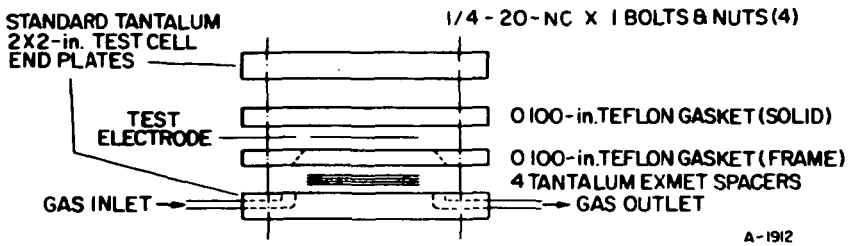


Figure 1. EXPLODED VIEW OF REACTOR

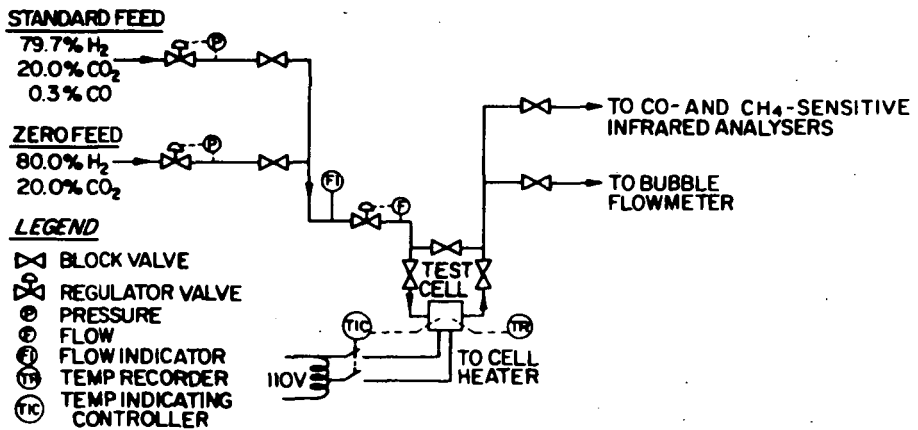


Figure 2. SCHEMATIC FLOW DIAGRAM OF EXPERIMENTAL SETUP

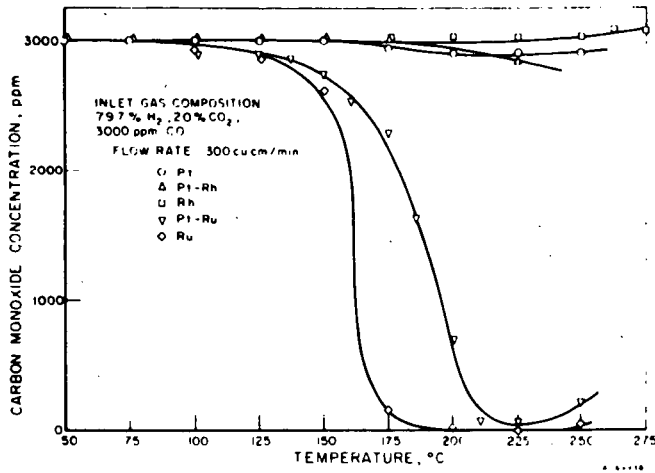


Figure 3. CARBON MONOXIDE IN EFFLUENT FROM METAL CATALYSTS

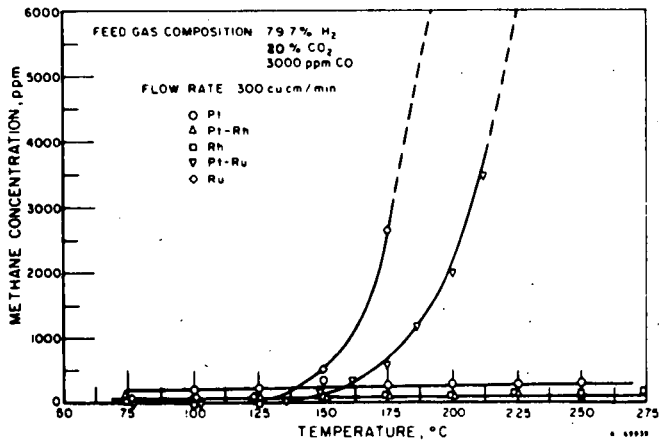


Figure 4. METHANE IN EFFLUENT FROM METAL CATALYSTS

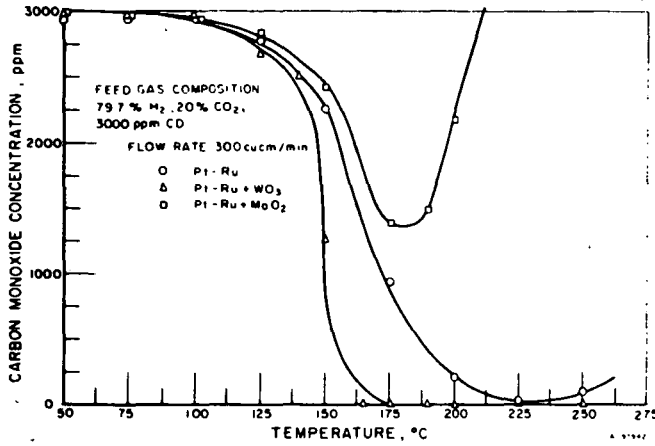


Figure 5. EFFECT OF ADMIX ON CARBON MONOXIDE IN EFFLUENT FROM Pt-Ru CATALYSTS

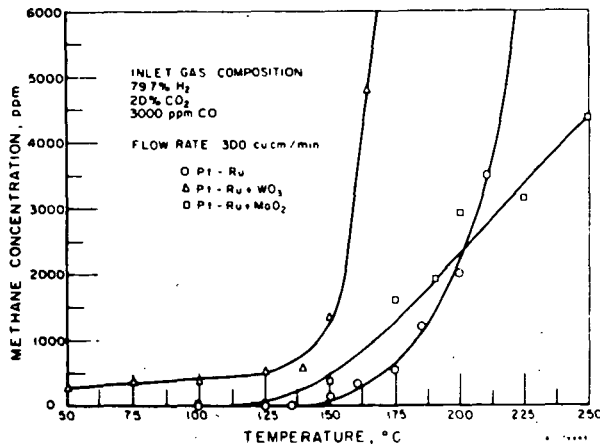


Figure 6. EFFECT OF ADMIX ON METHANE IN EFFLUENT FROM Pt-Ru CATALYSTS

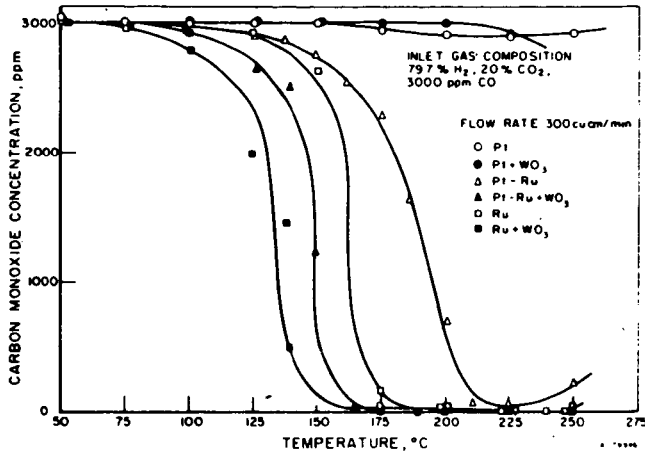


Figure 7. EFFECT OF WO₃ ADMIX ON CARBON MONOXIDE IN EFFLUENT FROM Ru-SYSTEM CATALYSTS

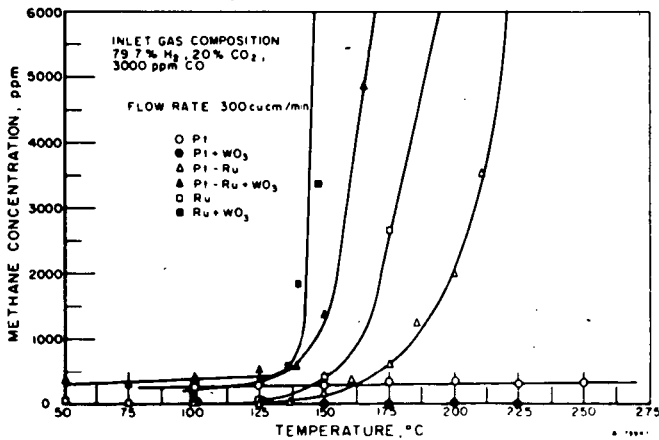


Figure 8. EFFECT OF WO₃ ADMIX ON METHANE IN EFFLUENT FROM Ru-SYSTEM CATALYSTS

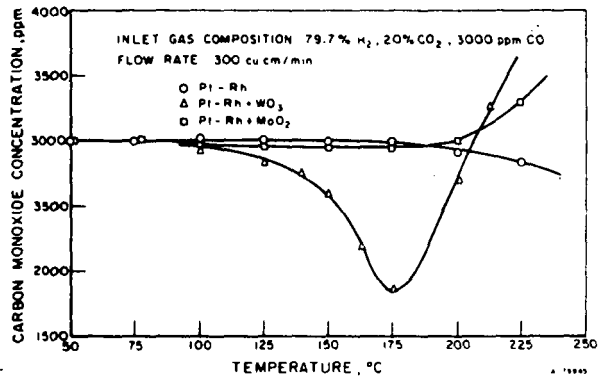


Figure 9. EFFECT OF ADMIX ON CARBON MONOXIDE IN EFFLUENT FROM Pt-Rh CATALYSTS

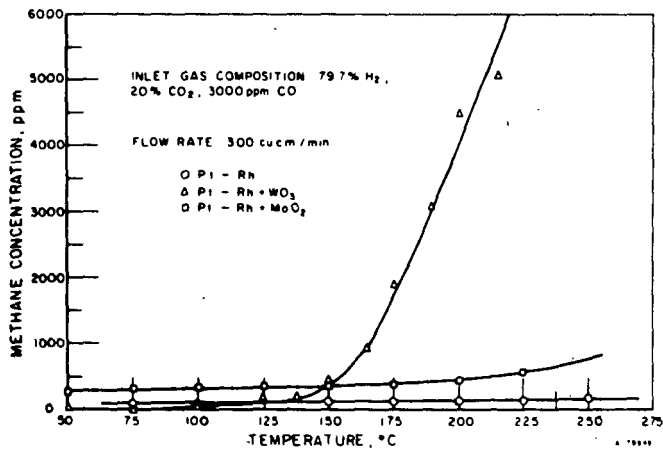


Figure 10. EFFECT OF ADMIX ON METHANE IN EFFLUENT FROM Pt-Rh CATALYSTS

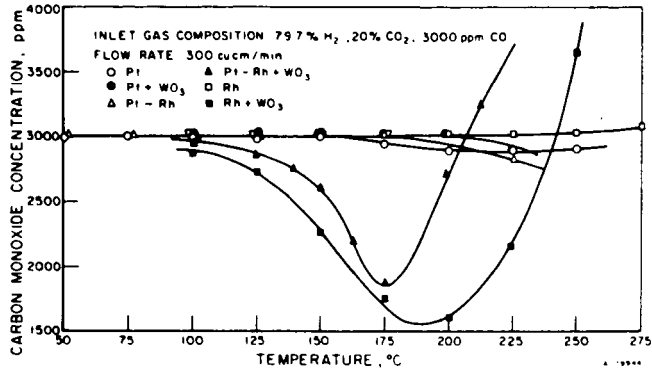


Figure 11. EFFECT OF WO_3 ADMIX ON CARBON MONOXIDE IN EFFLUENT FROM Rh-SYSTEM CATALYSTS

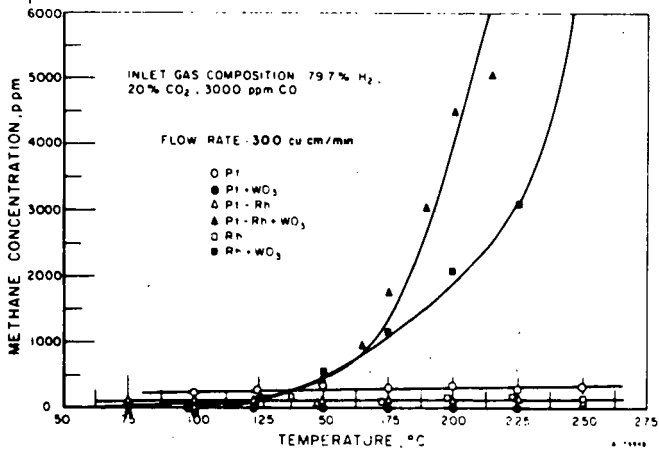


Figure 12. EFFECT OF WO_3 ADMIX ON METHANE IN EFFLUENT FROM Rh-SYSTEM CATALYSTS

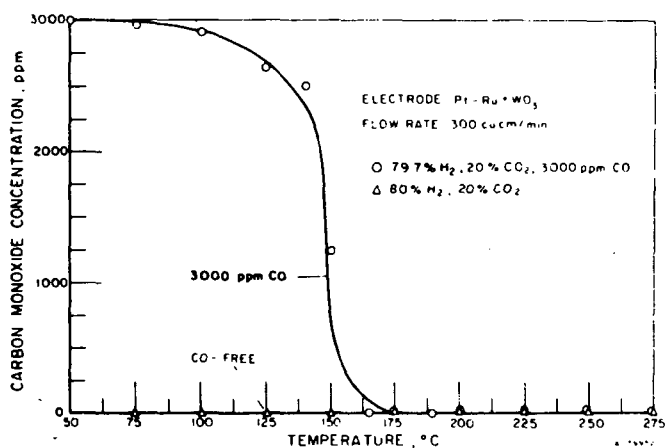


Figure 13. CARBON MONOXIDE IN EFFLUENT FROM Pt-Ru + WO₃ CATALYST WITH 3000-ppm CO AND CO-FREE FEEDS

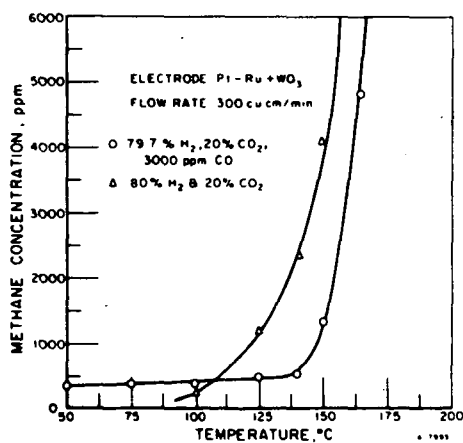


Figure 14. METHANE IN EFFLUENT FROM Pt-Ru + WO₃ CATALYST WITH 3000-ppm CO AND CO-FREE FEEDS

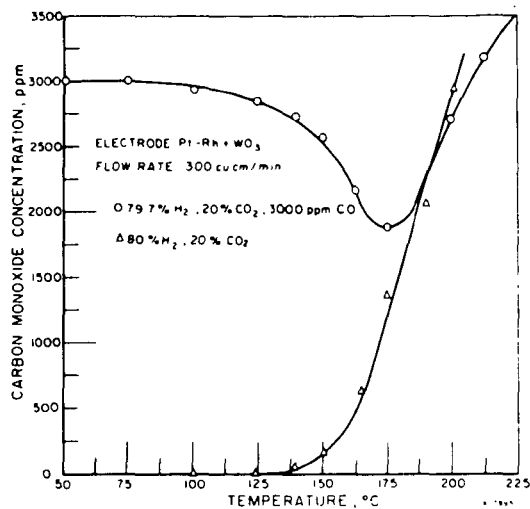


Figure 15. CARBON MONOXIDE IN EFFLUENT FROM Pt-Rh + WO₃ CATALYST WITH 3000-ppm CO AND CO-FREE FEEDS

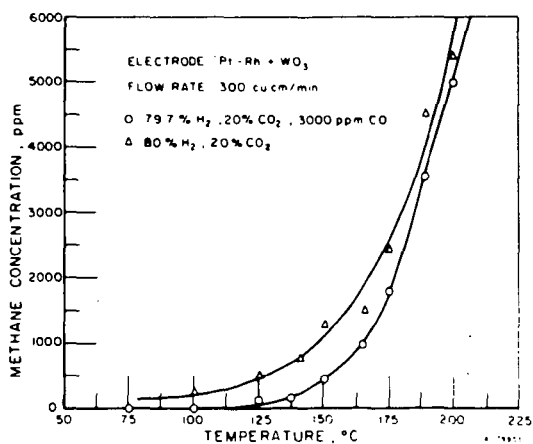


Figure 16. METHANE IN EFFLUENT FROM Pt-Rh + WO₃ CATALYST WITH 3000-ppm CO AND CO-FREE FEEDS

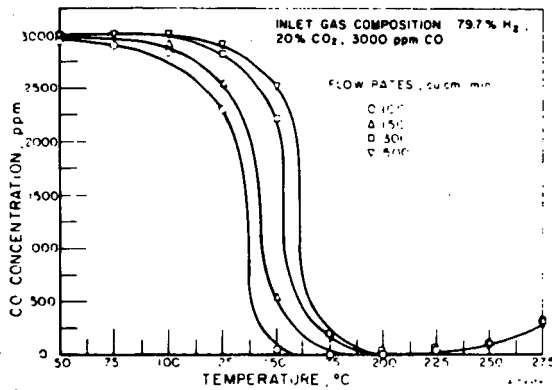


Figure 17. CARBON MONOXIDE IN EFFLUENT FROM Ru CATALYST AS A FUNCTION OF FLOW RATE

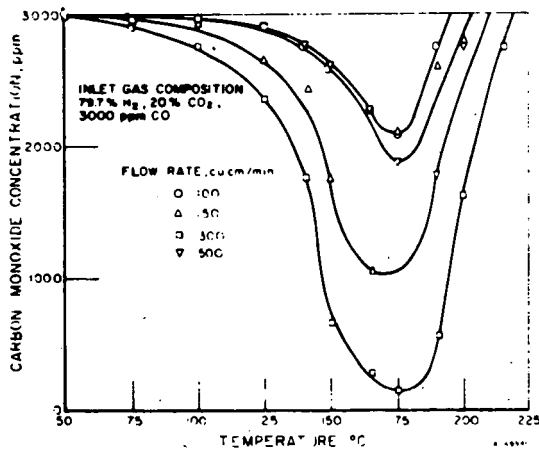


Figure 18. CARBON MONOXIDE IN EFFLUENT FROM Pt-Rh + WO₃ ELECTRODE AS A FUNCTION OF FLOW RATE